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Respirable Crystalline Silica Exposures During Asphalt Pavement Milling at Eleven Highway Construction Sites

Duane R. Hammond^a, Stanley A. Shulman^a, and Alan S. Echt^a

^aDivision of Applied Research and Technology, Engineering and Physical Hazards Branch, National Institute for Occupational Safety and Health

Abstract

Asphalt pavement milling machines use a rotating cutter drum to remove the deteriorated road surface for recycling. The removal of the road surface has the potential to release respirable crystalline silica, to which workers can be exposed. This paper describes an evaluation of respirable crystalline silica exposures to the operator and ground worker from two different half-lane and larger asphalt pavement milling machines that had ventilation dust controls and water-sprays designed and installed by the manufacturers.

Manufacturer A completed milling for eleven days at four highway construction sites in Wisconsin, while Manufacturer B completed milling for ten days at seven highway construction sites in Indiana. To evaluate the dust controls, full-shift personal breathing zone air samples were collected from an operator and ground worker during the course of normal employee work activities of asphalt pavement milling at eleven different sites.

Forty-two personal breathing zone air samples were collected over 21 days (sampling on an operator and ground worker each day). All samples were below 50 $\mu\text{g}/\text{m}^3$ for respirable crystalline silica, the National Institute for Occupational Safety and Health recommended exposure limit. The geometric mean personal breathing zone air sample was 6.2 $\mu\text{g}/\text{m}^3$ for the operator and 6.1 $\mu\text{g}/\text{m}^3$ for the ground worker for the Manufacturer A milling machine. The geometric mean personal breathing zone air sample was 4.2 $\mu\text{g}/\text{m}^3$ for the operator and 9.0 $\mu\text{g}/\text{m}^3$ for the ground worker for the Manufacturer B milling machine. In addition, upper 95% confidence limits for the mean exposure for each occupation were well below 50 $\mu\text{g}/\text{m}^3$ for both studies. The silica content in the bulk asphalt material being milled ranged from 7% to 23% silica for roads milled by Manufacturer A and from 5% to 12% silica for roads milled by Manufacturer B.

The results indicate that engineering controls consisting of ventilation controls in combination with water-sprays are capable of controlling occupational exposures to respirable crystalline silica generated by asphalt pavement milling machines on highway construction sites.

Address correspondence to: Duane R. Hammond, National Institute for Occupational Safety and Health, 1090 Tusculum Avenue Mail Stop R-5, Cincinnati, OH 45226; dhammond@cdc.gov.

DISCLAIMER

The findings and conclusions in this report are those of the authors and do not necessarily represent the views of the National Institute for Occupational Safety and Health.

Keywords

cold planers; dust control; recycled asphalt pavement; engineering controls

INTRODUCTION

Worker exposure to respirable crystalline silica can occur in agriculture, foundry work, hydraulic fracturing, mining, sandblasting, stone and granite work, and construction.^(1–13) Many construction tasks have been associated with overexposure to crystalline silica.^(14, 15) Among these tasks are tuck pointing, concrete sawing, concrete grinding, concrete scabbling, jackhammering, installing roof tiles, and abrasive blasting.^(16–24) Road milling has also been shown to result in overexposures to respirable crystalline silica.^(14, 25, 26) However, the three road-milling studies do not provide enough information about the operating parameters and engineering controls present on the milling machines to determine if the overexposures were due to a lack of effective controls or poor maintenance of the machines.

A variety of machinery are employed in asphalt pavement recycling, including cold-planers, heater-planers, cold-millers, and heater-scarifiers.⁽²⁷⁾ Cold-milling is the focus of this article. Cold-milling, which uses a toothed, rotating cutter drum to grind and remove the pavement to be recycled, is primarily used to remove surface deterioration on both petroleum-asphalt aggregate and Portland-cement concrete road surfaces.⁽²⁷⁾ Key components of a typical half-lane and larger asphalt pavement milling machine used for cold milling are shown in Figure 1.

Approximately 251,000 U.S. workers are employed in highway, street, and bridge construction.⁽²⁸⁾ A number of these workers use cold-milling machines or work in close proximity to the machine. Dust generated from the machines often contains respirable crystalline silica. This respirable dust can be transported by air currents to worker breathing zones near the milling machine.

The testing described in this article was coordinated by the Silica/Asphalt Milling Machine Partnership and is a result of a collaborative effort by labor, industry, and government to reduce respirable crystalline silica exposure during asphalt pavement milling in highway construction. This Silica/Asphalt Milling Machine Partnership is coordinated by the National Asphalt Pavement Association (NAPA) and includes all U.S. and foreign manufacturers of heavy construction equipment that currently sell pavement-milling machines to the U.S. market. In addition to NAPA and the equipment manufacturers, the Silica/Asphalt Milling Machine Partnership includes numerous paving contractors, the International Union of Operating Engineers, the Laborers International Union of North America, the Association of Equipment Manufacturers, and government organizations including the Occupational Safety and Health Administration (OSHA), the Federal Highway Administration, and the Centers for Disease Control and Prevention's (CDC's) National Institute for Occupational Safety and Health (NIOSH).

One of the aims of the Silica/Asphalt Milling Machine Partnership, and the focus of this article, is to evaluate engineering controls developed to reduce silica exposures among workers on half-lane and larger cold-milling machines. The engineering controls evaluated in this study included ventilation controls and water-spray systems used to cool the cutting teeth on asphalt pavement milling machines. The water-spray dust suppression controls were evaluated during previous field studies.⁽²⁹⁾ The capture efficiency of the ventilation dust controls were evaluated using tracer gas in a factory setting before field testing was conducted.^(30, 31) The manufacturers each optimized silica dust controls as part of the Partnership. The purpose of this final phase of testing was to verify the effectiveness of the final engineering control configuration before installation on an entire fleet of milling machines.

Silica Health Effects and Exposure Limits

Inhalation of respirable crystalline silica can cause silicosis, a debilitating and potentially fatal lung disease. Silica exposure has also been associated with lung cancer, chronic obstructive pulmonary disease, renal disease, and other adverse health outcomes.⁽³²⁾ During the period from 1990 through 1999, at least one-third of decedents with silicosis had worked in construction or mining.⁽³³⁾ The NIOSH recommended exposure limit (REL) for respirable crystalline silica is 50 $\mu\text{g}/\text{m}^3$ as a time-weighted average (TWA) determined during a full-shift personal breathing zone (PBZ) sample. This REL is applicable for most workers who work up to a 10-hr workday during a 40-hr workweek to reduce the risk of developing silicosis, lung cancer, and other adverse health effects.⁽³²⁾

The current OSHA permissible exposure limit (PEL) for respirable dust containing crystalline silica for the construction industry is measured by impinger sampling. In the construction industry, the PELs for cristobalite and quartz are the same.⁽³⁴⁾

Since the PELs were adopted, the impinger sampling method has been rendered obsolete by gravimetric sampling.⁽³⁵⁾ OSHA currently instructs its compliance officers to apply a conversion factor when converting between gravimetric sampling and the particle count standard when characterizing construction operation exposures.⁽³⁶⁾

On September 12, 2013, OSHA published a Notice of Proposed Rulemaking (NPRM) for occupational exposure to respirable crystalline silica. The NPRM was published in the *Federal Register* and proposes a PEL of 50 $\mu\text{g}/\text{m}^3$ for respirable crystalline silica as an 8-hr TWA exposure.⁽³⁷⁾

The American Conference of Governmental Industrial Hygienists (ACGIH) Threshold Limit Value (TLV) for quartz and cristobalite (respirable fraction) is 25 $\mu\text{g}/\text{m}^3$.⁽³⁸⁾ The documentation to the TLV states that “it is the concern about fibrosis (silicosis) and the precedent inflammatory process resulting from silica exposures, and the association of inflammation and fibrosis with lung cancer that leads to this recommendation.”⁽³⁹⁾

Description of the Dust Controls

A NIOSH document *Best Practice Engineering Control Guidelines to Control Worker Exposure to Respirable Crystalline Silica during Asphalt Pavement Milling* provides

detailed recommendations for ventilation controls and water-sprays on asphalt milling machines.⁽⁴⁰⁾ The ventilation control recommendations focus on providing an enclosure around the drum housing and conveyors, proper hood and duct design, airflow capacity, durability of the duct and fan, and measures to prevent clogging of the ventilation control. To contain silica dust, the manufacturers designed their systems to remove air and maintain negative air pressure in the drum housing of the milling machine to contain the source of dust generation. Milling machine manufacturers also optimized water-sprays along the primary and secondary conveyor in addition to the original water applications applied only to the drum to cool cutting teeth.

The equipment provided by Manufacturer A and used during the first 11 days at four sites was an asphalt milling machine with dual diesel engines capable of producing 534 kilowatt (kW) (716 horsepower (HP)) that comply with emissions standard EC Stage 3b / US Tier 4i. The Manufacturer A asphalt milling machine had a 2 m 79-inch) wide cutter drum with a ventilation control and water spray dust suppression. The ventilation control used a fan and flexible hose system to draw air through a hood through the top cover of the primary conveyor nearest the drum housing which created negative air pressure in both the primary conveyor and drum housing areas. The ventilation control did not include any filtration but exhausted the air at the end of the secondary conveyor away from any workers. The water spray dust suppression system included water applied to the drum housing to cool the teeth and suppress dust as well as additional water spray nozzles in the primary conveyor to suppress dust along the conveyed path of recycled asphalt pavement. The maximum water flow rate was 18 gallons per minute but was adjusted by the operator depending on milling machine speed and depth of cut.

The equipment provided by Manufacturer B and used during the last 10 days at 7 sites was an asphalt milling machine with an 2.2 m 86-inch) wide cutter drum and a diesel engine that provides 462 kW (620 HP) at 1850 rpm. The Manufacturer B asphalt milling machine was fitted with a water spray system and ventilation controls consisting of a hydraulic powered 5.2 kW (7-hp) Ilmeg fan connected to a 6-inch (15 centimeter (cm)) diameter duct leading to a manifold that split the flow into two 4-inch (10 cm) diameter ducts that exhausted air at the top of the secondary conveyor. The ventilation control used a fan and flexible hose system to draw air through multiple slots through the top cover of the primary conveyor near the drum housing and near the conveyor transition area which created negative air pressure in both the primary conveyor and drum housing areas. The ventilation control did not include any filtration but exhausted the air at the end of the secondary conveyor away from any workers. The water spray dust suppression system included water applied to the drum housing and along the primary conveyor and secondary conveyors as shown in Figures 5, 6, and 7 of NIOSH Publication No. 2015-105.⁽⁴⁰⁾ The maximum water flow rate was 23 gallons per minute but was adjusted by the operator depending on milling machine speed and depth of cut.

Description of the Operator and Ground Worker Tasks

PBZ air samples for respirable crystalline silica were collected from the milling machine operator and ground worker during the course of normal employee work activities of asphalt

pavement milling. The milling machine operator would typically spend the entire shift on the operator bridge of the milling machine which is located above the cutter drum housing. The operator is responsible for adjusting controls such as milling machine speed, steering, depth of cut, water flow to cutting teeth, and maintaining communications with dump truck drivers using hand signals to fill trucks with recycled asphalt pavement. The ground worker operates the ground controls on the back sides of the milling machine and would typically spend most of the shift walking next to the machine at ground level several feet away from the drum housing. The primary task of the ground worker is to operate ground level milling machine controls associated with the quality of cut for the road surface being milled. The ground worker may also be responsible for tasks such as coordinating traffic flow around the machine especially when milling through intersections, connecting the hose from the water truck to the milling machine, and various additional tasks.

METHODS

PBZ air samples for respirable crystalline silica were collected from the milling machine operator and ground worker using respirable dust cyclones (model GK2.69, BGI Inc., Waltham, MA) at a flow rate of 4.2 liters/minute (L/min) with battery-operated sampling pumps (Gilian model GilAir® Plus, Sensidyne®, Clearwater, FL) calibrated before and after each day's use. A sampling pump was clipped to each sampled employee's belt and connected via Tygon® tubing and a tapered Leur-type fitting to a pre-weighed, 37-mm diameter, 5-micron (µm) pore-size polyvinyl chloride filter supported by a backup pad in a three-piece filter cassette sealed with a cellulose shrink band (in accordance with NIOSH Methods 0600 and 7500).^(41, 42) The front portion of the cassette was removed and the cassette was attached to a respirable dust cyclone and placed in the breathing zone of the worker.

The filter samples were analyzed for respirable particulates in accordance with NIOSH Method 0600,⁽⁴¹⁾ for which the limit of detection (LOD) was 30 µg/sample, and the limit of quantitation (LOQ) was 110 µg/sample. The results were blank corrected with the average of the media blanks.

Crystalline silica analysis of filter samples was performed using X-ray diffraction in accordance with NIOSH Method 7500.⁽⁴²⁾ The LODs for quartz, cristobalite and tridymite are 5 µg/sample, 10 µg/sample, and 10 µg/sample, respectively. The LOQs for quartz, cristobalite, and tridymite are 17 µg/sample, 33 µg/sample, and 33 µg/sample, respectively.

Bulk samples were analyzed in accordance with NIOSH Method 7500, for which the LODs for quartz, cristobalite, and tridymite in bulk samples were 0.3%, 0.3%, and 0.5%, respectively. The LOQs for quartz, cristobalite, and tridymite in bulk samples were 0.83%, 0.83%, and 1.7%, respectively.

Statistical Methodology

The statistical criterion used for effective performance of each manufacturer's control system is that the upper 95% confidence limit for the arithmetic mean of each occupation's PBZ air sampling results should be less than the NIOSH REL of 50 µg/m³. These upper

confidence limits for each occupation and manufacturer are computed assuming the lognormal distribution for the PBZ samples.⁽⁴³⁾ Tolerance limits for 95% of the population of PBZ air samples are also provided. The goal of the study was to compare results with the NIOSH REL and not to compare manufacturers against each other.

The PBZ air sampling results were analyzed separately for each occupation and manufacturer. The methods available for obtaining confidence limits for the arithmetic mean of lognormal distributions are limited to relatively simple models.^(44–46) The methodology used is for models with a mean and two variance components and is described in more detail in Appendix C of NIOSH Publication 2015-105 which uses the “Method of Variance Estimates Recovery” (MOVER).⁽⁴⁰⁾

The arithmetic mean of the log normally distributed PBZ air sampling results for each manufacturer’s occupation is shown in Equation 1:

$$\exp(\mu + 0.5(\sigma_s^2 + \sigma_{sd}^2)), \quad (1)$$

where,

μ = log scale mean;

σ_s^2 = between site variance;

σ_{sd}^2 = within site variance.

The upper confidence limits in Tables II and IV were calculated using Equation 2, which is based on a statistical model with one mean and two variance components, as in Equation 1 above:.

$$\begin{aligned} \text{UCL2} = & (\bar{x} + 0.5s_{\bar{x}_s}^2 + 0.5(1 - n\text{bar})\text{astd}_{ws}^2 + \\ & \sqrt{\left(s_{\bar{x}_s} \frac{t(0.95, df1)}{\sqrt{n_{\text{sites}}}}\right)^2 + 0.5^2 + s_{\bar{x}_s}^4 \left(\frac{df1}{\text{chisq}(0.05, df1)} - 1\right)^2 + (0.5(1 - n\text{bar}))^2 \text{astd}_{ws}^4 \left(\frac{df2}{\text{chisq}(1 - 0.05, df2)} - 1\right)^2} \end{aligned} \quad (2)$$

where,

\bar{x} = mean of log-scale site means of PBZ samples; Tables II and IV geometric means obtained by exponentiation;

$s_{\bar{x}_s}^2$ = sample variance of log-scale site means of PBZ samples;

astd_{ws}^2 = pooled within-site variance on log-scale, computed by weighting within-site variances by their degrees of freedom, summing, and dividing by sum of degrees of freedom; geometric standard deviation for within sites in Tables II and IV were obtained by exponentiating the square root of this value;

n_{sites} = number of sites;

$df1 = n_{\text{sites}} - 1$;

$df2$ = number of measurements-number of sites;

\bar{n} = average of reciprocals of number of days at each site;

$t(0.95, df1)$ = 95th percentile of t distribution, $df1$ degrees of freedom;

$\text{chisq}(0.05, df1)$ = 5th percentiles of the chi square distribution, $df1$ degrees of freedom;

$\text{chisq}(1-0.05, df2)$ = 95th percentiles of the chi square distribution, $df2$ degrees of freedom;

$UCL_o = e^{UCL2}$ is the upper confidence limit for the arithmetic mean of occupation o

Geometric standard deviations between sites are the exponentiated values

$\sqrt{s_{\bar{x}_s}^2 - \bar{n} \times \text{astd}_{ws}^2}$. GSD-based RSD values in Tables II and IV were calculated using the formula $\text{sqrt}(e^{[\ln(\text{GSD}) \times \ln(\text{GSD})] - 1})$.⁽⁴³⁾

The upper tolerance limits in Tables II and IV also use the MOVER. The aim is to determine the largest confidence level $(1-\alpha)$ for which 95% of PBZ measurements from the entire population (from which the chosen sites and workers come) are less than the REL. The upper tolerance limits use the exponentiated values of equation 11 in Krishnamoorthy et. al.⁽⁴⁴⁾ The quantities used in eq (2) are also used for these limits. Ogden et al. recommend using between 70% and 80% upper tolerance limits for 95% of the population in compliance decisions for small sample sizes.⁽⁴⁷⁾

The air sampling data for the two manufacturers differ in number of days at sites. Manufacturer A included three sites with three days of sampling and a fourth site with two days. Manufacturer B included five sites with one day of sampling and two sites with multiple days. For Manufacturer B, within sites variance is based on the two sites with multiple days.

For Manufacturer A, there were three different operators and five different ground workers. Some individuals worked at one site, but others worked at multiple sites. Manufacture B used the same operator for all sites, and the same ground worker for the first six sites with a different one at the seventh site.

SAS Proc Mixed was used to evaluate the between worker variance components separately for each study.⁽⁴⁸⁾ The dependent variable in each study model was all log scale PBZ samples for the two occupations. Including both occupations allows for more statistical power. Whereas the model used for Equation 2 had one mean and two variance components, this new model had two means, one for each occupation, and four variance components: between site and within site variances, as in expression (1), and the variance between workers in occupations and the residual variance. For both Manufacturer A and B, the test of between worker variance components did not yield statistically significant results (5% level) via F test⁽⁴⁸⁾ or likelihood ratio⁽⁴⁹⁾; the between worker variance component was therefore

removed. That variance component is also not needed in the model for Equation 2. Thus, for each occupation in each study, the between site and within site variance components were the two components used. The need to use relatively simple models restricts the number of components to two.

Manufacturer A had one day with sample values less than the limit of detection (LOD) for both workers, for which the substitution $MCD/2$ was made, where MDC is the concentration corresponding to the sample when the LOD is used as the reported mass.⁽⁵⁰⁾

In multiple regression with seven explanatory variables (discussed in a section below), the log scale average of the two PBZ samples per day was used as the dependent variable. All subsets regression via the Cp criterion⁽⁵¹⁾ was used to reduce the number of variables in the model. Each retained numerical variable's effect was quantified by taking the difference, 75th – 25th percentile values of the variable, multiplying the difference by the variable's regression coefficient, and exponentiating. This is the effect of the 75th relative to 25th percentile of this variable when all other variables are held constant (Table VI).

RESULTS

NIOSH researchers conducted 42 full-shift PBZ air sampling for respirable crystalline silica from the operator and ground worker on two different asphalt pavement milling machines. The sampling was conducted over 21 days at 11 highway construction sites during the course of normal employee work activities of asphalt pavement milling. A milling machine provided by Manufacturer A was used during the first 11 days at 4 sites, and a milling machine provided by Manufacturer B was used for milling during the remaining 10 days at 7 sites.

Diversity in asphalt pavement milling conditions were present. The selected sites included diversity in day and night milling with milling during night shifts occurring in 8 of the 21 shifts. The study included diversity of shift lengths with 79% of the shifts lasting between 8 to 12 hours. Of the 42 PBZ air samples, 38 of the 42 PBZ air samples were from shifts lasting longer than 7 hours, 33 of the 42 PBZ air samples were from shifts lasting longer than 8 hours, 20 of the 42 PBZ air samples were from shifts lasting longer than 9 hours, 11 of the 42 PBZ air samples were from shifts lasting longer than 10 hours, and 5 of the 42 PBZ air samples were from shifts lasting longer than 11 hours.

Diverse types of highway construction sites were selected. The roads milled included rural highways, city streets, a parking lot, and a major freeway. Recycled asphalt pavement removal depths included typical 1.5 to 3 inch (3.81 to 7.62 cm) mill and fill removals as well as full-depth removals of up to 11 inches (28 cm) of recycled asphalt pavement. Mill and fill removals accounted for 13 of the 21 shifts with typical milling machine speeds ranging from 40 to 80 feet per minute (fpm) (0.2 to 0.41 meters per second (m/s). Removals of 4 to 6 inches (10 to 15 cm) of recycled asphalt pavement accounted for 3 of the 21 shifts with typical milling speeds ranging from 40 to 50 fpm (0.2 to 0.25 m/s). Full depth removals of 9 to 11 inches (23 to 28 cm) of recycled asphalt pavement accounted for 4 of the 21 shifts with milling machine speeds ranging from 20 to 30 fpm (0.1 to 0.15 m/s). On one of the 21 days

of milling, the machine was used to remove only 1-inch (2.54 cm) of asphalt pavement at an average speed of 12 fpm (0.06 m/s) which was not considered to be representative of typical asphalt pavement milling for that 6-hour shift.

Weather

The weather was recorded from the National Oceanic and Atmospheric Administration (NOAA) fixed weather station nearest to each evaluated site. Ambient temperatures ranged from 0°C to 33°C and average wind speeds per shift ranged from 0.9 to 5.0 m/s.

Manufacturer A PBZ Air Sampling Results

Full-shift PBZ silica air sampling results during the 11 days of air sampling at 4 sites for the operator and ground worker using the Manufacturer A asphalt milling machine are shown in Table I along with the silica content in the bulk and filter samples for each day. At the 4 sites studied, the percent bulk silica content in the roads being milled ranged from 7 and 23%, with an average of 16%. Silica content in the PBZ filter air samples for the operator and ground worker using the Manufacturer A asphalt milling machine ranged from below the LOD to 14%. The 22 full-shift PBZ air sampling results for the operator and ground worker using the Manufacturer A milling machine ranged from below the minimum detectable concentration to 13 $\mu\text{g}/\text{m}^3$.

Table II shows the means and upper 95% confidence limits for the two occupations and other summary statistics. The geometric mean respirable crystalline silica exposure for the operator was 6.2 $\mu\text{g}/\text{m}^3$ with an upper 95% confidence limit for the arithmetic mean of 28.2 $\mu\text{g}/\text{m}^3$. The geometric mean respirable crystalline silica exposure for the ground worker was 6.1 $\mu\text{g}/\text{m}^3$ with an upper 95% confidence limit for the arithmetic mean of 13.5 $\mu\text{g}/\text{m}^3$. The upper confidence limits are less than the NIOSH REL of 50 $\mu\text{g}/\text{m}^3$.

Table II also shows the confidence of being less than the NIOSH REL for 95% of the population of values from which manufacturer A data were drawn. For the ground worker, 95% of the population is less than the REL with greater than 95% confidence, and the confidence for the operator is about 87%.

Manufacturer B PBZ Air Sampling Results

Full-shift PBZ air sampling for silica during the ten days of sampling at seven sites for the operator and ground worker using the Manufacturer B asphalt milling machine are shown in Table III along with the silica content in the bulk and filter samples for each day. At the 7 sites studied, the percent bulk silica content in the road material being milled ranged from 5 and 12%, with an average of 8%. Silica content in the PBZ filter air samples for the operator and ground worker using the Manufacturer B asphalt milling machine ranged from below the LOD to 9%.

The 20 full-shift PBZ air sampling results for the operator and ground worker using the Manufacturer B milling machine ranged from below the LOD to 13 $\mu\text{g}/\text{m}^3$ with the exception of second day of sampling where the PBZ air sample for the ground worker was 24 $\mu\text{g}/\text{m}^3$. The third day of sampling (site 3) resulted in non-detectable concentrations and

was not used in the statistical analysis partly because the 6-hour shift included 3-hours of downtime and partly because the low milling speed and 1-inch (2.54 cm) removal depth are not typical of asphalt milling.

Table IV shows the means and upper 95% confidence limits for the two occupations and other summary statistics. The geometric mean respirable crystalline silica exposure for the operator was $4.2 \mu\text{g}/\text{m}^3$ with an upper 95% confidence limit for the arithmetic mean of $11.8 \mu\text{g}/\text{m}^3$. The geometric mean respirable crystalline silica exposure for the ground worker was $9.0 \mu\text{g}/\text{m}^3$ with an upper 95% confidence limit for the arithmetic mean of $29.8 \mu\text{g}/\text{m}^3$. Thus, the upper 95% confidence limits are statistically significantly less than the NIOSH REL of $50 \mu\text{g}/\text{m}^3$.

Table IV also shows the confidence of being less than the REL for 95% of the population of values from which manufacturer B data were drawn. For the operator, 95% of the population of silica measurements were less than the REL with more than 95% confidence, and for the ground worker the confidence is about 80%.

Investigation of Effect of Explanatory Variables

The seven explanatory variables (Table V) were manufacturer (A or B), average cut depth, average machine speed, whether work was day or night, average wind speed, average temperature, and % silica in bulk samples. Table V has 20 rows, since 11 days were sampled for manufacturer A and 9 days for manufacturer B (after omitting one day). The dependent variable was the log scale average of the operator and ground worker PBZ samples for each day. The explanatory variables were used in multiple regression.

The reduced statistical model excluded average temperature and average wind speed. Except for the variable that allowed for difference in study means, the estimated regression coefficients are shown in Table VI. The variable concerning study means, though needed in the model, was not statistically significant at the 10% level, whereas all other included variables were. For the three continuous variables, the estimated 75th to 25th percentile factor effect is between 2 and 3. Also, day milling leads to about half the PBZ levels as night milling. The data set is small and these results need verification from additional work.

DISCUSSION

Both manufacturers designed their dust controls using recommendations provided as part of the Silica/Asphalt Milling Machine Partnership. These recommendations are documented in the NIOSH Publication No. 2015-105.⁽⁴⁰⁾ A goal of the Partnership was to statistically compare the air sampling results during field testing with the NIOSH REL so that milling machine manufacturers would have statistical confidence that the dust controls would protect workers when implemented on all new asphalt milling machines of similar model type for that manufacturer. Appendix C of NIOSH Publication No. 2015-105 provides the full development of the statistical method and Appendix B of NIOSH Publication 2015-105 provides site selection considerations for field testing of engineering controls on asphalt milling machines before those machines are implemented across a manufacturer's entire fleet. Site selection recommendations such as weather, silica content, downtime, and shift

length were met for all test days except for day 3 of Manufacturer B. Each manufacturer chose to have sampling conducted for more days and sites than the minimum recommend by NIOSH Publication No. 2015-105.⁽⁴⁰⁾

The evaluated ventilation controls on both asphalt pavement milling machines performed well at capturing dust generated in the drum housing and releasing the dust at the top of the secondary conveyor at a location away from the workers. The ventilation controls were effective at maintaining PBZ air samples to levels well below the NIOSH REL of 50 $\mu\text{g}/\text{m}^3$ for respirable crystalline silica. However, three out of the 21 evaluated shifts included times when the crew was milling into the wind while dust released at the outlet of the ventilation control blew back toward the operator and ground worker. It was estimated that dust blew back toward the machines for less than one hour during two of the shifts and approximately three hours for another shift. Dust blowing back toward the operator and ground worker for a portion of the three shifts did not appear to influence exposures, but was annoying for the operator and the ground worker. When milling into the wind, the operators decided to temporarily turn off the ventilation control until wind conditions changed. Turning off the ventilation control when milling into the wind worked well for the limited amount of time that unfavorable wind conditions were present during three of the 21 days of sampling and did not appear to influence exposures. It is possible that future milling studies could occur during longer periods of unfavorable wind conditions or the operator could forget to turn the ventilation control back on after short periods of unfavorable wind conditions. After this study, both milling machine manufacturers made plans to equip their ventilation controls with technology to automatically turn the dust control back on after it has been off for 1 hour.

CONCLUSIONS

The 42 PBZ air samples were collected during 21 days at 11 sites and included diversity in typical asphalt pavement milling conditions. The roads being milled included rural highways, city streets, a parking lot, and a major freeway. Milling depths ranged from typical one to three inch (2.54 to 7.62 cm) mill and fill removals as well as full-depth removals of up to eleven inches (28 cm) of recycled asphalt pavement. The selected sites included diversity in day and night milling. Weather conditions included a wide range of ambient temperatures and wind conditions. The study included diversity of shift lengths with the majority of shifts lasting between 8 to 12 hours. Respirable crystalline silica PBZ air samples were below 50 $\mu\text{g}/\text{m}^3$ for the operator and ground worker over all 21 evaluated shifts covering a wide range of typical conditions for asphalt pavement milling. For each occupation and each manufacturer the 95% upper confidence limits for the arithmetic mean exposure were less than 50 $\mu\text{g}/\text{m}^3$. This suggests that for the population from which the sites were drawn, there is high probability that the average exposure of workers is less than 50 $\mu\text{g}/\text{m}^3$.

The results indicate that the evaluated ventilation dust controls in combination with water-sprays are capable of controlling occupational exposures to respirable crystalline silica during a wide range of typical highway construction jobs using asphalt pavement milling machines. Following this testing, the manufacturers of both asphalt pavement milling

machines made plans to include the ventilation as a standard feature on all new half-lane and larger asphalt pavement milling machines. Additional asphalt milling machine manufacturers who are Silica/Asphalt Pavement Milling Machine Partnership members also made commitments to perform similar field testing and implement silica dust controls on their milling machines.

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REFERENCES

1. Nieuwenhuijsen MJ, Noderer KS, Schenker MB, Vallyathan V, Olenchock S. Personal exposure to dust, endotoxin and crystalline silica in California agriculture. *Ann Occup Hyg.* 1999; 43(1):35–42. [PubMed: 10028892]
2. Rosenman KD, Reilly MJ, Rice C, Hertzberg V, Tseng CY, Anderson HA. Silicosis among foundry workers. Implication for the need to revise the OSHA standard. *Am J Epidemiol.* 1996; 144(9):890–900. [PubMed: 8890667]
3. Esswein EJ, Breitenstein M, Snawder J, Kiefer M, Sieber WK. Occupational exposures to respirable crystalline silica during hydraulic fracturing. *J Occup Environ Hyg.* 2013; 10(7):347–356. [PubMed: 23679563]
4. Laney AS, Petsonk EL, Attfield MD. Pneumoconiosis among underground bituminous coal miners in the United States: is silicosis becoming more frequent? *Occup Environ Med.* 2010; 67(10):652–656. [PubMed: 19773275]
5. Centers for Disease, C., and Prevention. Silicosis screening in surface coal miners--Pennsylvania, 1996–1997. *MMWR Morb Mortal Wkly Rep.* 2000; 49(27):612–615. [PubMed: 10914927]
6. Verma DK, Rajhans GS, Malik OP, des Tombe K. Respirable dust and respirable silica exposure in Ontario gold mines. *J Occup Environ Hyg.* 2014; 11(2):111–116. [PubMed: 24369933]
7. Grove T, Dyk TV, Franken A, Du Plessis J. The Evaluation and Quantification of Respirable Coal and Silica Dust Concentrations: A Task-based Approach. *J Occup Environ Hyg.* 2013
8. Radnoff DL, Kutz MK. Exposure to crystalline silica in abrasive blasting operations where silica and non-silica abrasives are used. *Ann Occup Hyg.* 2014; 58(1):19–27. [PubMed: 24353009]
9. Healy CB, Coggins MA, Van Tongeren M, MacCalman L, McGowan P. Determinants of respirable crystalline silica exposure among stoneworkers involved in stone restoration work. *Ann Occup Hyg.* 2014; 58(1):6–18. [PubMed: 23997236]
10. Phillips ML, Johnson DL, Johnson AC. Determinants of respirable silica exposure in stone countertop fabrication: a preliminary study. *J Occup Environ Hyg.* 2013; 10(7):368–373. [PubMed: 23668829]
11. Radnoff D, Todor MS, Beach J. Occupational Exposure to Crystalline Silica at Alberta Work Sites. *J Occup Environ Hyg.* 2014
12. Radnoff D, Todor MS, Beach J. Exposure to Crystalline Silica at Alberta Work Sites: Review of Controls. *J Occup Environ Hyg.* 2015; 12(6):393–403. [PubMed: 25625185]
13. Gottesfeld P, Andrew D, Dalhoff J. Silica Exposures in Artisanal Small-Scale Gold Mining in Tanzania and Implications for Tuberculosis Prevention. *J Occup Environ Hyg.* 2015; 12(9):647–653. [PubMed: 25897484]
14. Rappaport SM, Goldberg M, Susi P, Herrick RF. Excessive exposure to silica in the US construction industry. *Ann Occup Hyg.* 2003; 47(2):111–122. [PubMed: 12581996]

15. Beaudry C, Lavoue J, Sauve JF, Begin D, Senhaji Rhazi M, Perrault G, et al. Occupational exposure to silica in construction workers: a literature-based exposure database. *J Occup Environ Hyg.* 2013; 10(2):71–77. [PubMed: 23252413]
16. National Institute for Occupational Safety and Health (NIOSH). DHHS (NIOSH), Publication No. 2000-113. Cincinnati, Ohio: NIOSH; 2000. Respirable crystalline silica exposures during tuck pointing.
17. Thorpe A, Ritchie AS, Gibson MJ, Brown RC. Measurements of the effectiveness of dust control on cut-off saws used in the construction industry. *Ann Occup Hyg.* 1999; 43(7):443–456. [PubMed: 10582028]
18. Echt A, Sieber WK. Control of silica exposure from hand tools in construction: grinding concrete. *Appl Occup Environ Hyg.* 2002; 17(7):457–461. [PubMed: 12083163]
19. Shepherd S, Woskie S. Controlling dust from concrete saw cutting. *J Occup Environ Hyg.* 2013; 10(2):64–70. [PubMed: 23252479]
20. Akbar-Khanzadeh F, Brillhart RL. Respirable crystalline silica dust exposure during concrete finishing (grinding) using hand-held grinders in the construction industry. *Ann Occup Hyg.* 2002; 46(3):341–346. [PubMed: 12176721]
21. Echt A, Sieber W, Jones A, Jones E. Control of silica exposure in construction: scabbling concrete. *Appl Occup Environ Hyg.* 2002; 17(12):809–813. [PubMed: 12495590]
22. Echt A, Sieber K, Jones E, Schill D, Lefkowitz D, Sugar J, et al. Control of respirable dust and crystalline silica from breaking concrete with a jackhammer. *Appl Occup Environ Hyg.* 2003; 18(7):491–495. [PubMed: 12791543]
23. Hall RM, Achutan C, Sollberger R, McCleery RE, Rodriguez M. Exposure assessment for roofers exposed to silica during installation of roof tiles. *J Occup Environ Hyg.* 2013; 10(1):D6–D10. [PubMed: 23186147]
24. Glindmeyer HW, Hammad YY. Contributing factors to sandblasters' silicosis: inadequate respiratory protection equipment and standards. *J Occup Med.* 1988; 30(12):917–921. [PubMed: 3068336]
25. Linch KD. Respirable concrete dust--silicosis hazard in the construction industry. *Appl Occup Environ Hyg.* 2002; 17(3):209–221. [PubMed: 11871757]
26. Valiante DJ, Schill DP, Rosenman KD, Socie E. Highway repair: a new silicosis threat. *Am J Public Health.* 2004; 94(5):876–880. [PubMed: 15117715]
27. Public Works. Pavement recycling. Public Works 126. 1995
28. United States Census Bureau. Highway, street, and bridge construction. Washington D.C.: U.S. Department of Commerce; 2012. Census Statistics of US Businesses NAICS 237310.
29. National Institute for Occupational Safety and Health (NIOSH). DHHS (NIOSH), EPHB Report No. 282-18a. Cincinnati, OH: 2011. Dust-control technology for asphalt-pavement milling controlled-site testing at State Highway 47, Bonduel, Wisconsin.
30. National Institute for Occupational Safety and Health (NIOSH). DHHS (NIOSH), EPHB Report No. 282-19a. Cincinnati, OH: 2011. A laboratory evaluation of capture efficiencies of the vacuum cutting system on a Wirtgen W 250 cold milling machine at Payne & Dolan Inc., Racine, Wisconsin.
31. National Institute for Occupational Safety and Health (NIOSH). DHHS (NIOSH), EPHB Report No. 282-21a. Cincinnati, OH: 2013. A laboratory evaluation of a local exhaust ventilation system on a Roadtec cold milling machine at Roadtec, Chattanooga, Tennessee.
32. National Institute for Occupational Safety and Health (NIOSH). DHHS (NIOSH). Cincinnati, OH: NIOSH; 2002. NIOSH hazard review: health effects of occupational exposure to respirable crystalline silica. Publication No. 2002-129
33. National Institute for Occupational Safety and Health (NIOSH). DHHS (NIOSH). Cincinnati, OH: NIOSH; 2007. Silicosis: most frequently recorded industries on death certificate, U.S. residents age 15 and over, selected states and years, 1990–1999, Table 3–6. In: NIOSH work-related lung disease surveillance report 2007. Publication No. 2008–143a
34. CFR. U.S. Government Printing Office, 29 CFR 1926.55. Washington, D.C.: 2003. Code of Federal Regulations.

35. Occupational Safety and Health Administration (OSHA). Appendix F: permissible exposure limits for construction and maritime. In: Memorandum of May 2, 1996, from Joseph A. Dear. Occupational Safety and Health Administration, to regional administrators. 1996
36. Occupational Safety and Health Administration (OSHA). Occupational Safety and Health Administration, CPL 03-00-007. Washington, D.C.: 2008. Appendix E: conversion factor for silica PELs in construction and maritime. In: National emphasis program—crystalline silica.
37. Occupational Safety and Health Administration (OSHA). Occupational Exposure to Respirable Crystalline Silica, A Proposed Rule by the Occupational Safety and Health Administration on 09/12/2013. 78 Fed. Reg. 56274. 2013
38. ACGIH. 2013 Threshold Limit Values (TLVs) and Biological Exposure Indices (BEIs). Cincinnati, OH: ACGIH; 2013.
39. ACGIH. 2010 Documentation to the TLV silica, crystalline – α -quartz and cristobalite. Cincinnati, OH: ACGIH; 2010.
40. National Institute for Occupational Safety and Health (NIOSH). DHHS (NIOSH) Publication No. 2015–105. Cincinnati, OH: NIOSH; 2015. Best Practice Engineering Control Guidelines to Control Worker Exposure to Respirable Crystalline Silica during Asphalt Pavement Milling.
41. National Institute for Occupational Safety and Health (NIOSH). Publication No. 81-123. Cincinnati, OH: NIOSH; 1998. Particulates not otherwise regulated, respirable.
42. National Institute for Occupational Safety and Health (NIOSH). Publication No. 2003-154. Cincinnati, OH: NIOSH; 2003. Silica, crystalline, by XRD (filter redeposition).
43. Rappaport, SM.; Kuppe, LL. Quantitative Exposure Assessment. Stephen Rappaport: 2008.
44. Krishnamoorthy K, Peng J. Approximate one-sided tolerance limits in random effects model and in some mixed models and comparisons. *Journal of Statistical Computation and Simulation*. 2014; 85(8):1651–1666.
45. Krishnamoorthy K, Mathew T. One-Sided Tolerance Limits in Balanced and Unbalanced One-Way Random Models Based on Generalized Confidence Intervals. *Technometrics*. 2004; 46(1):44–52.
46. Liao CT, Lin TY, Iyer HK. One- and Two-Sided Tolerance Intervals for General Balanced Mixed Models and Unbalanced One-Way Random Models. *Technometrics*. 2005; 47(3):323–335.
47. Ogden T, Lavoué J. 2011 William P. Yant Award Lecture. *J Occup Environ Hyg*. 2012; 9(4):D63–D70. [PubMed: 22428624]
48. Littell, RC.; Milliken, GA.; Stroup, WW.; Wolfinger, RD.; Schabenberger, O. SAS System for Mixed Models. 2nd. Cary, NC: SAS Institute; 2006. p. 80
49. Scheipl F, Greven S, Küchenhoff H. Size and power of tests for a zero random effect variance or polynomial regression in additive and linear mixed models. *Computational Statistics & Data Analysis*. 2008; 52(7):3283–3299.
50. Hornung RW, Reed LD. Estimation of Average Concentration in the Presence of Nondetectable Values. *Appl Occup Environ Hyg*. 1990; 5(1):46–51.
51. Daniel, C.; aWF. Fitting Equations to Data. John Wiley and Sons, Inc.; 1980.

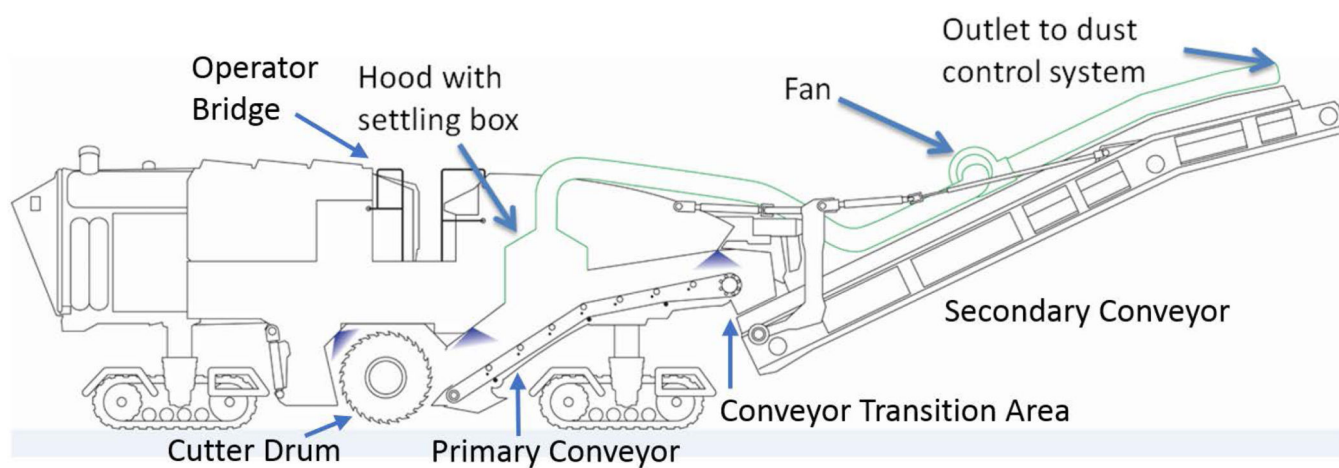


Figure 1.
Half-lane and larger asphalt pavement milling machine (Illustration by NIOSH)

Table I

Manufacturer A Full-shift PBZ silica air sampling results in $\mu\text{g}/\text{m}^3$

| Silica Results | Highway 92 (Mount Horeb, Wisconsin) | | | | Eclipse Center Parking lot (Beloit, Wisconsin) | | Highway 50 (Kenosha, Wisconsin) | | Multiple residential city streets (Menomonee Falls, Wisconsin) | | |
|------------------|--|-----------|----------|--------|--|--------------------|------------------------------------|-----------------|---|---------|-----------|
| | Tuesday | Wednesday | Thursday | Friday | Saturday | Wednesday night | Thursday night | Friday night | Monday | Tuesday | Wednesday |
| Operator | | | | | | | | | | | |
| Concentration | ND ^A | 3 | 6 | 9 | 10 | 6 | 9 | 11 | 13 | 3 | 8 |
| % silica | ND ^A | 11% | 12% | 14% | 12% | 6% | 7% | 10% | 8% | 4% | 6% |
| Sample time | 561 | 700 | 284 | 530 | 455 | 493 | 436 | 480 | 537 | 650 | 550 |
| MDC ^B | 2.1 | 1.7 | 4.2 | 2.2 | 2.6 | 2.4 | 2.7 | 2.4 | 2.3 | 1.9 | 2.2 |
| Ground Worker | | | | | | | | | | | |
| Concentration | ND ^A | 5 | 7 | 8 | 7 | 6 | 9 | 10 | 10 | 4 | 7 |
| % silica | ND ^A | 11% | 13% | 14% | 12% | 6% | 6% | 9% | 7% | 4% | 5% |
| Sample time | 560 | 518 | 279 | 527 | 455 | 500 | 440 | 476 | 525 | 646 | 552 |
| MDC ^B | 2.1 | 2.3 | 4.3 | 2.3 | 2.6 | 2.4 | 2.7 | 2.5 | 2.3 | 1.9 | 2.2 |
| % silica bulk | 18% | 19% | 20% | 23% | 23% | 9.6% | 15% | 17% | 16% | 7% | 10% |

^A ND=non-detect (there was no quartz detected in the filter samples on June 26)

^B Field limit of detection or Minimum Detectable Concentration (MDC) = (LOD of 5 $\mu\text{g}/\text{sample}$)/(volume in cubic meters)

Table II

Manufacturer A PBZ statistics in $\mu\text{g}/\text{m}^3$ with estimates

| Occupation | Number of samples | Number samples < LOD ^A | Maximum ($\mu\text{g}/\text{m}^3$) | Number of sites | AM ($\mu\text{g}/\text{m}^3$) Original scale | GM ($\mu\text{g}/\text{m}^3$) | Between Site GSD | Within Site GSD | Total GSD | GSD-based total RSD (relative standard deviation) | Upper 95% confidence for arithmetic mean ($\mu\text{g}/\text{m}^3$) ^B | %Confidence that 95% of population < REL ^C |
|------------|-------------------|-----------------------------------|--------------------------------------|-----------------|--|---------------------------------|------------------|-----------------|-----------|---|--|---|
| Operator | 11 | 1 | 13 | 4 | 7.2 | 6.2 | 1.50 | 1.77 | 2.02 | 80% | 28.2 | 87% |
| Ground man | 11 | 1 | 10 | 4 | 6.6 | 6.1 | 1.20 | 1.67 | 1.72 | 58% | 13.5 | >95% |

^A MDC /sqrt(2) was substituted for these two samples for use in the calculations.

^B Equation 2 was used separately for each occupation.

^C Equation 11 in Krishnamoorthy et. al was used separately for each occupation. (44)

Table III

Manufacturer B Full-shift PBZ silica air sampling results in $\mu\text{g}/\text{m}^3$

| | US-31N Carmel, IN | Washington and S HS Rd, Indianapolis, IN | East McCarty, Indianapolis, IN | South Ford Rd, Zionsville, IN | I-465 between Allisonville Rd and I-69, Indianapolis, IN | US-24, Wabash, IN | US-24, Ft. Wayne, IN |
|-------------------------------------|----------------------|---|---|--|--|-------------------------|----------------------|
| Silica ($\mu\text{g}/\text{m}^3$) | 18-Sep | 19-Sep | 20-Sep | 21-Sep | 27-Sep | 4-Oct | 10-Oct 11-Oct 12-Oct |
| Operator | | | | | | | |
| Concentration | 4 | 5 | ND ^A | 11 | 2 | 2 | 7 6 3 |
| % silica | 6% | 4% | ND ^A | 6% | 2% | 2% | 3% 4% 3% |
| Sample time | 484 | 611 | 338 | 540 | 612 | 676 | 533 559 519 |
| MDC ^B | 2.5 | 2.0 | 3.5 | 2.2 | 1.9 | 1.8 | 2.2 2.1 2.3 |
| Ground worker | | | | | | | |
| Concentration | 12 | 24 | ND ^A | 12 | 4 | 4 | 6 13 8 |
| % silica | 9% | 6% | ND ^A | 8% | 3% | 3% | 3% 3% 5% |
| Sample time | 482 | 614 | 370 | 539 | 620 | 685 | 533 556 519 |
| MDC ^B | 2.5 | 1.9 | 3.2 | 2.2 | 1.9 | 1.7 | 2.2 2.1 2.3 |
| % silica bulk | 5.0% | 5.4%, 12% ^B | 7.2% | 11.4% | 5.5% | 5.8% | 8.1% 8.9% 9.1% |

^AND=non-detect (there was no quartz detected in the filter samples on September 20th, site 3); this was not a typical work day and results were not used in the statistical analysis.

^BField limit of detection or Minimum Detectable Concentration (MDC) = (LOD of 5 $\mu\text{g}/\text{sample}$)/(volume in cubic meters)

^C12% silica content on Washington Street and 5.4% silica content on High School Road

Manufacturer B PBZ statistics in $\mu\text{g}/\text{m}^3$

Table IV

| Occupation | Number of Samples | Number < LOD ^A | Maximum ($\mu\text{g}/\text{m}^3$) | Number of sites Used | AM ($\mu\text{g}/\text{m}^3$) Original scale | GM ($\mu\text{g}/\text{m}^3$) | Between Site GSD | Within Site GSD | Total GSD | GSD-based total RSD, Relative standard deviation | Upper 95% confidence limit for arithmetic mean ($\mu\text{g}/\text{m}^3$) ^B | % Confidence, 95% of population <REL ^C |
|---------------|-------------------|---------------------------|--------------------------------------|----------------------|--|---------------------------------|------------------|-----------------|-----------|--|--|---|
| Operator | 10 | 1 | 11 | 6 | 4.9 | 4.2 | 1.70 | 1.43 | 1.90 | 71% | 11.8 | >95% |
| Ground worker | 10 | 1 | 24 | 6 | 10.8 | 9.0 | 1.86 | 1.35 | 1.99 | 78% | 29.8 | 80% |

^AThe two values for site 3 were omitted from the statistical analysis because the work done was atypical.

^BEquation (2) was used separately for each occupation.

^CEquation 11 in Krishnamoorthy et. al was used separately for each occupation. (44)

Explanatory Variables

Table V

| Study | Site | Day at site | Average Cut Depth (inches) | Average Machine Speed (ft/minute) | Day or night | Average Wind Speed(m/s) | Temperature Average (degrees C) | %Silica in Bulk Samples |
|-------|----------------|-------------|----------------------------|-----------------------------------|--------------|-------------------------|---------------------------------|-------------------------|
| A | 1 | 1 | 2 | 40 | d | 1.5 | 26 | 18 |
| A | 1 | 2 | 2 | 40 | d | 4.9 | 25 | 19 |
| A | 1 | 3 | 2 | 40 | d | 3.6 | 28 | 20 |
| A | 2 | 1 | 1.5 | 60 | d | 1.2 | 21 | 23 |
| A | 2 | 2 | 1.5 | 40 | d | 1.2 | 21 | 23 |
| A | 3 | 1 | 2 | 45 | n | 3.1 | 23 | 9.6 |
| A | 3 | 2 | 2 | 45 | n | 3.7 | 27 | 15 |
| A | 3 | 3 | 2 | 40 | n | 1.8 | 24 | 17 |
| A | 4 | 1 | 6 | 40 | d | 1.5 | 24 | 16 |
| A | 4 | 2 | 4 | 40 | d | 2.5 | 22 | 7 |
| A | 4 | 3 | 4 | 50 | d | 1 | 21 | 10 |
| B | 1 | 1 | 9 | 30 | d | 4.8 | 16 | 5 |
| B | 2 | 1 | 11 | 20 | d | 2.7 | 11 | 8.7 |
| B | 4 ⁺ | 1 | 1.5 | 80 | d | 0.9 | 11 | 11.4 |
| B | 5 | 1 | 9 | 20 | n | 1 | 19 | 5.5 |
| B | 5 | 2 | 9 | 20 | n | 1.3 | 16 | 6.3 |
| B | 6 | 1 | 1.5 | 80 | d | 4 | 16 | 5.8 |
| B | 7 | 1 | 1.5 | 60 | n | 3.3 | 4 | 8.1 |
| B | 7 | 2 | 1.5 | 60 | n | 4.3 | 12 | 8.9 |
| B | 7 | 3 | 1.5 | 60 | n | 2.4 | 5 | 9.1 |

* Average of the operator and ground worker samples

⁺ Site 3 data were not used because work conditions were not typical.

Table VI

Estimates of Explanatory Variable Regression Coefficients

| Variable | Estimated Regression Coefficient | 25 th percentile of variable | 75 th percentile of variable | Regression Coefficient \times (75 th percentile - 25 th percentile) | Ratio of 75 th to 25 th Predicted Values, When Other Variables Are Held Constant (Exponentiated Value of Column 5) |
|--------------------------------|----------------------------------|---|---|---|--|
| Average Machine Speed (ft/min) | 0.047 | 40 | 60 | 0.949 | 2.583 |
| Average Cut Depth (in) | 0.291 | 1.5 | 4.5 | 0.874 | 2.397 |
| %Silica in Bulk | 0.078 | 7.83 | 17.25 | 0.738 | 2.092 |
| Day relative to night work | -0.659 | | | | 0.518 ^A |

^AThe exponentiated value of -0.659 is 0.518. This means that the average day TWAs are about 0.518 of the average night TWAs, based on the statistical model.